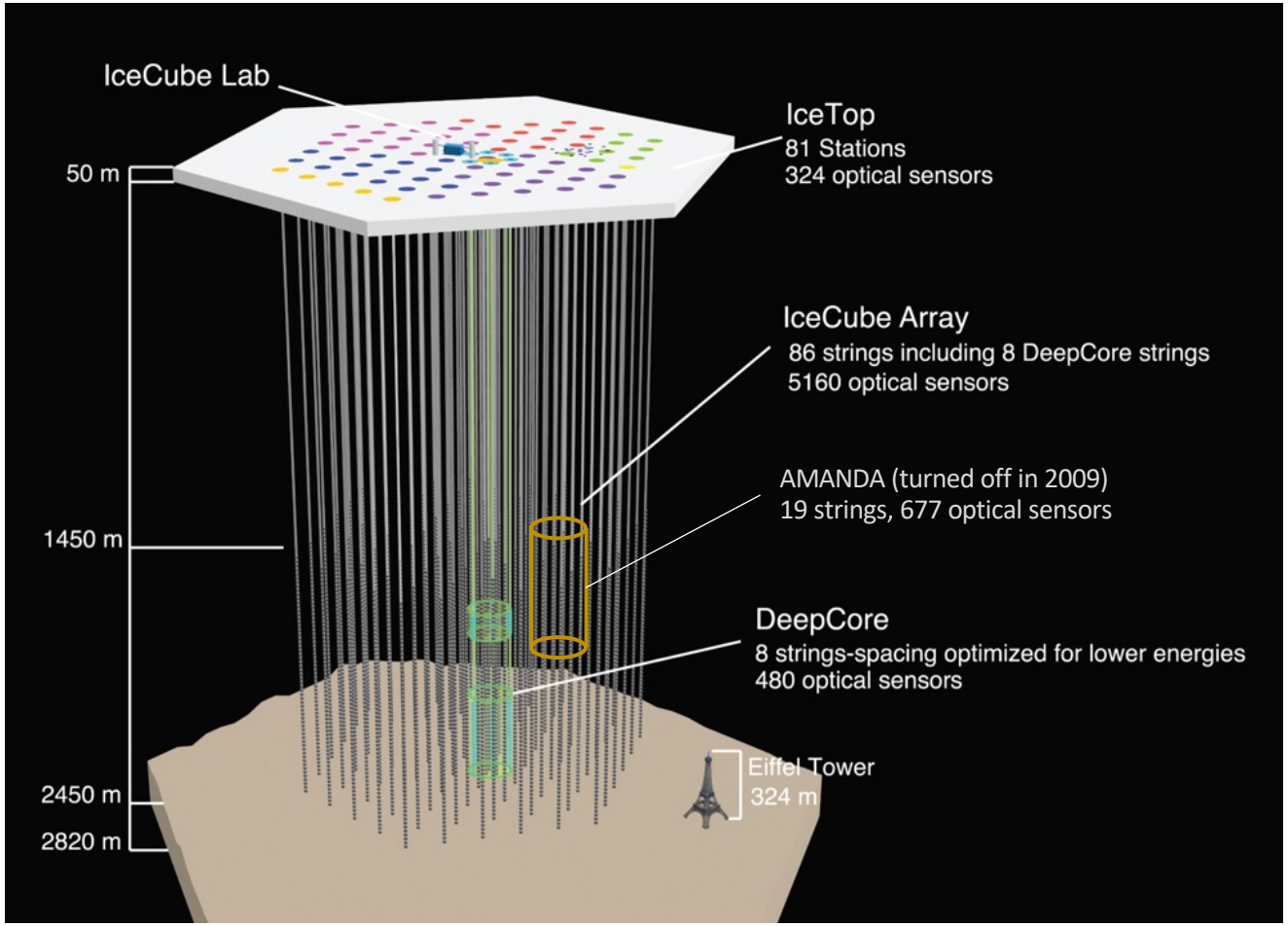
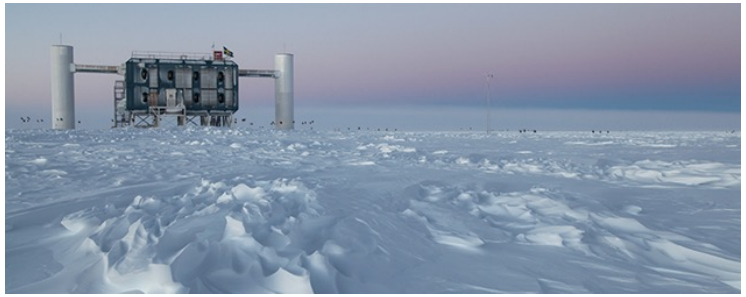
IceCube model of optical properties of the South Pole ice: ice layer tilt

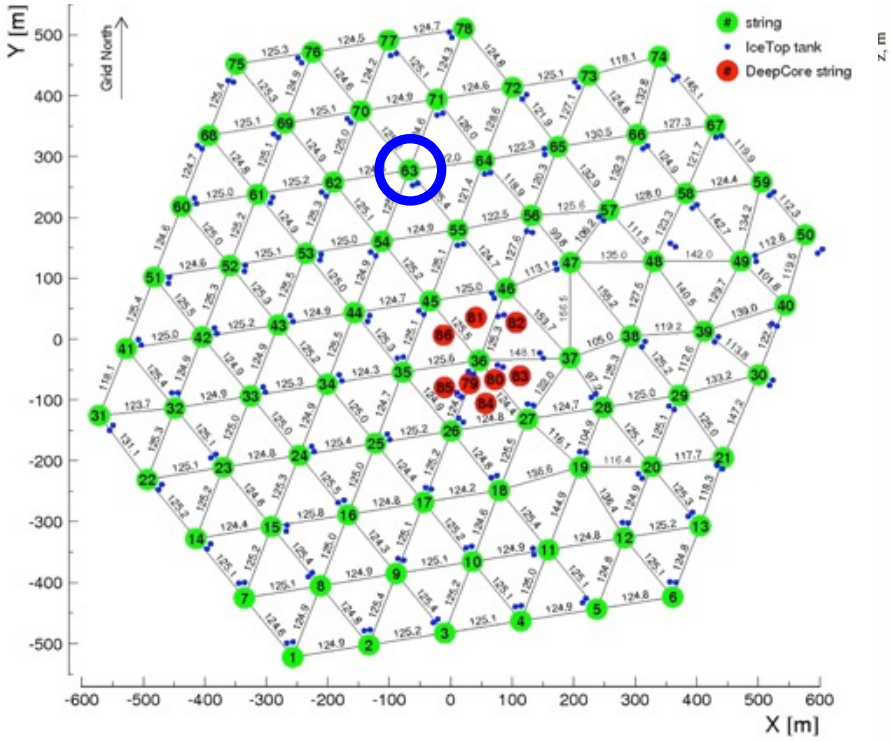


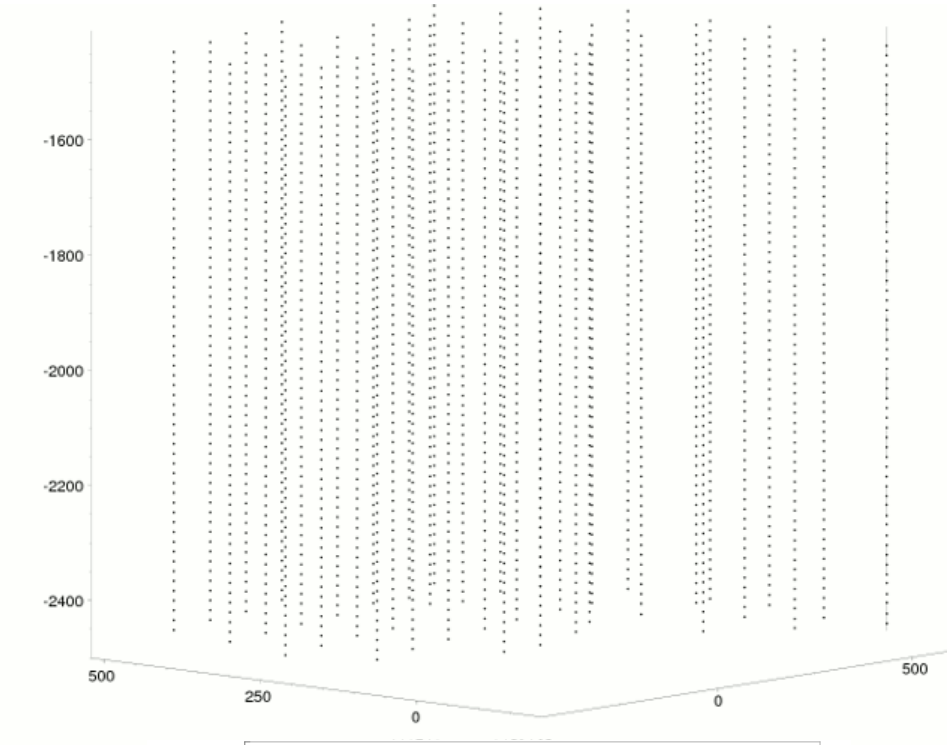


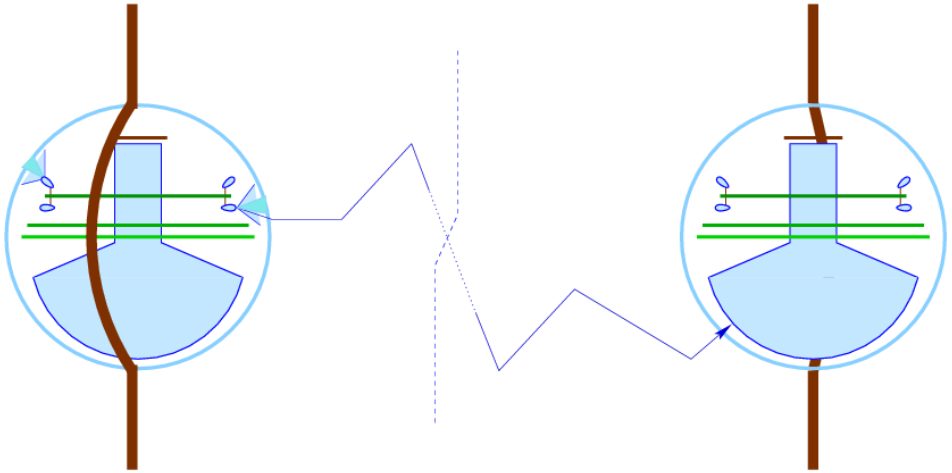


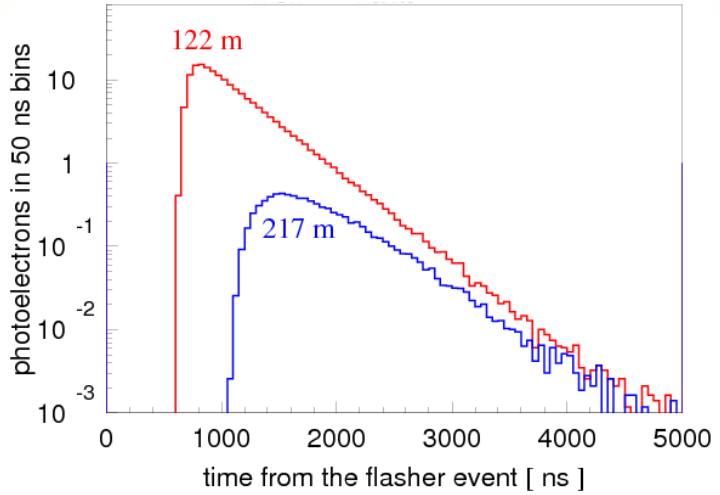
Dmitry Chirkin, UW Madison,
Martin Rongen, JGU Mainz,
for the IceCube collaboration

Fitting ice to in-situ data

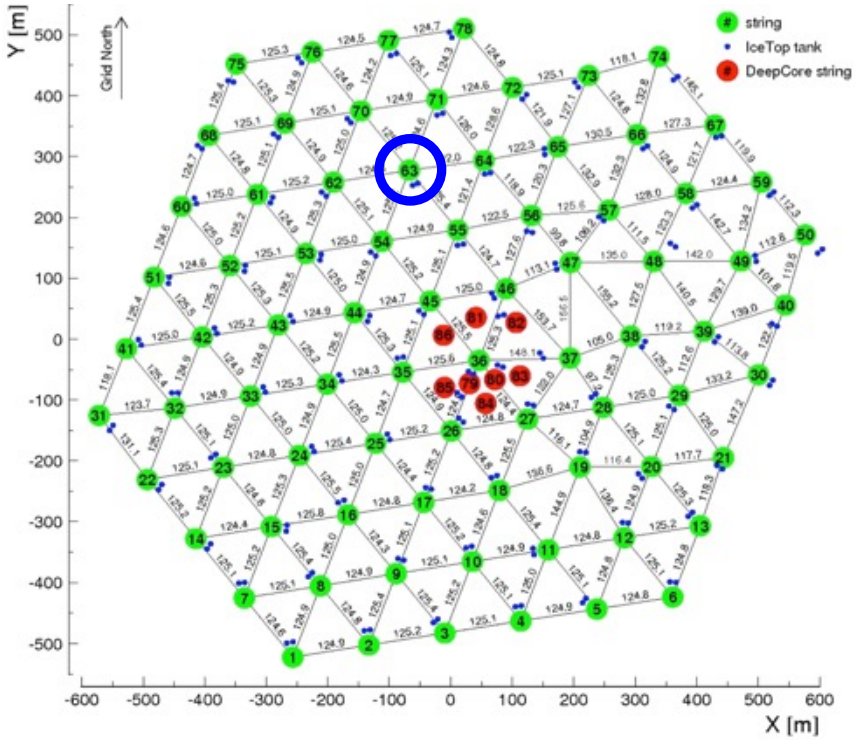


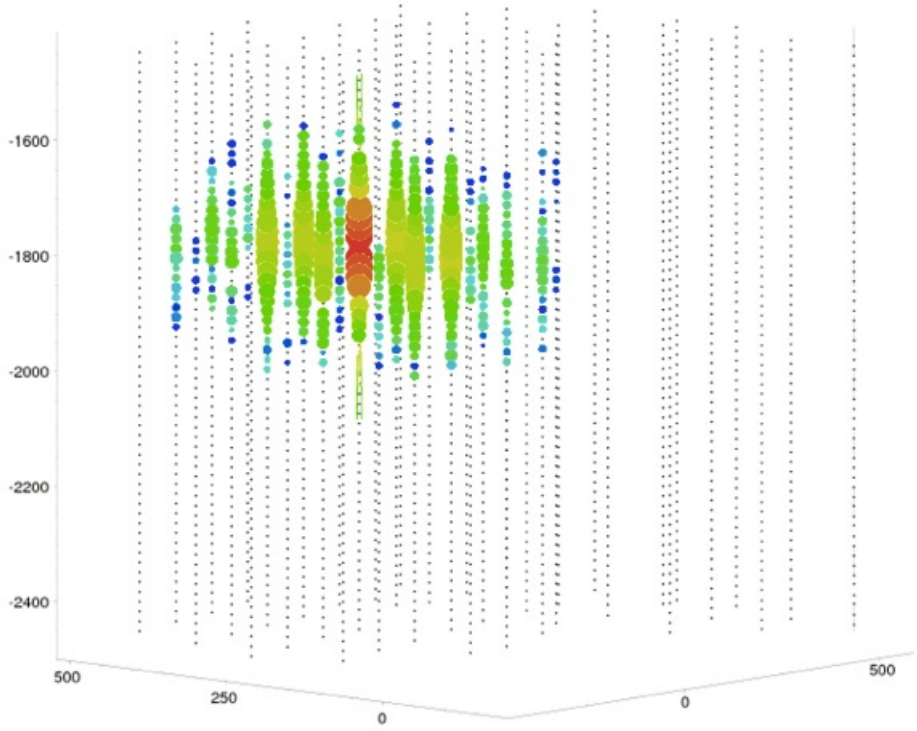


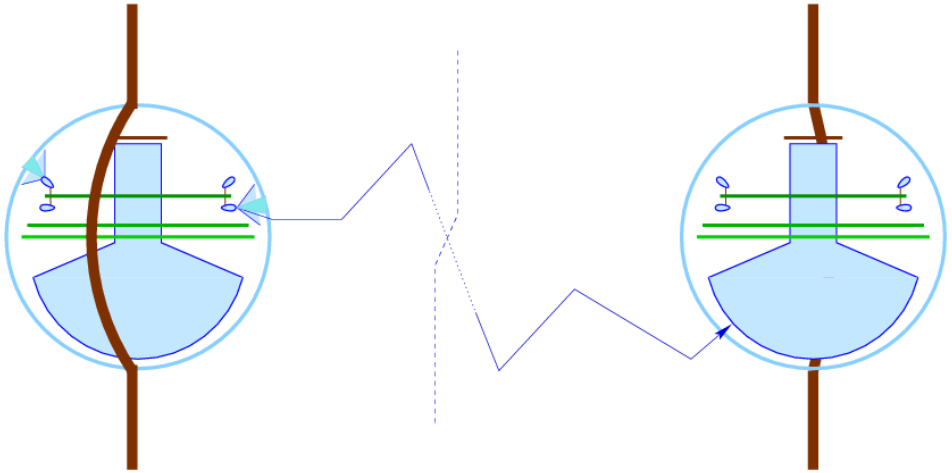


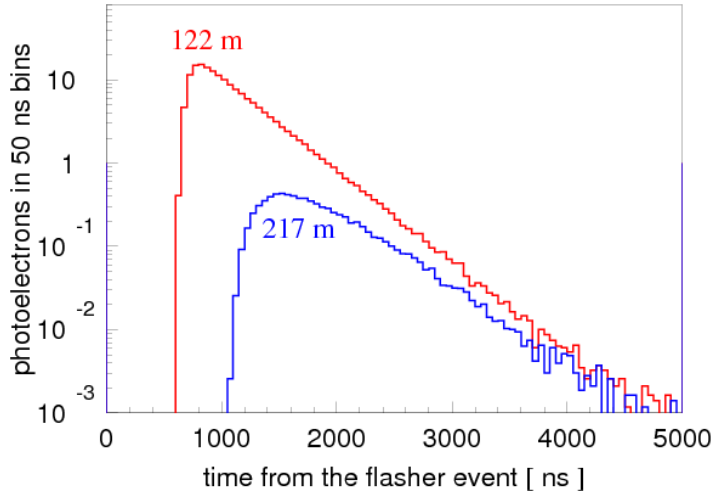


Fitting ice to in-situ data

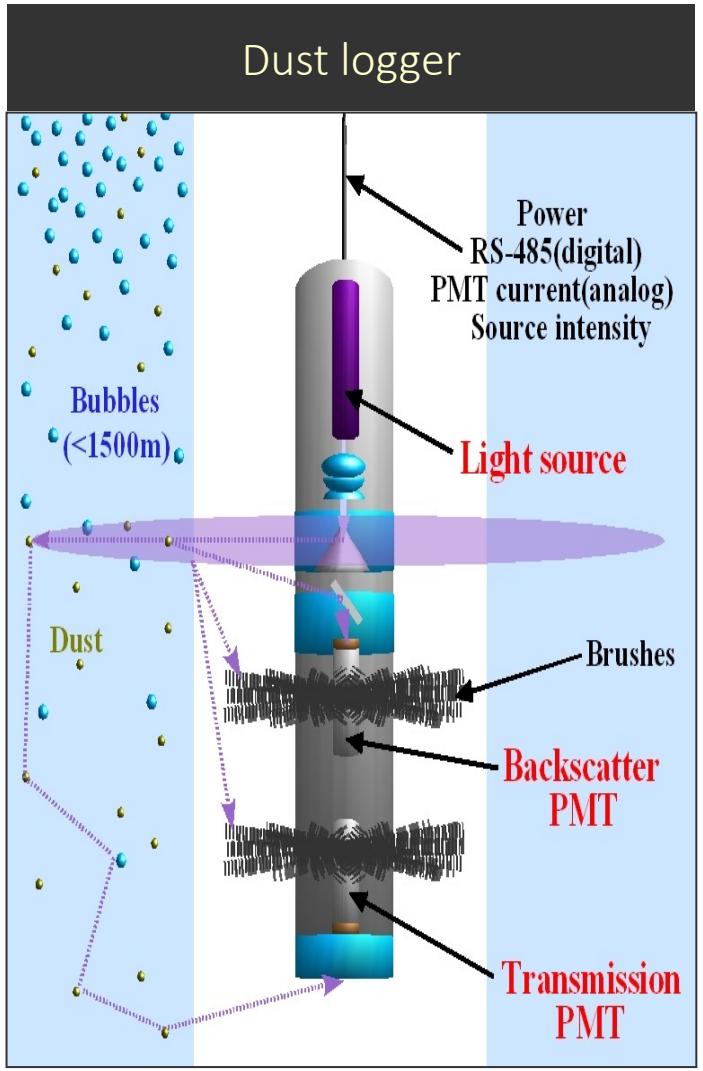


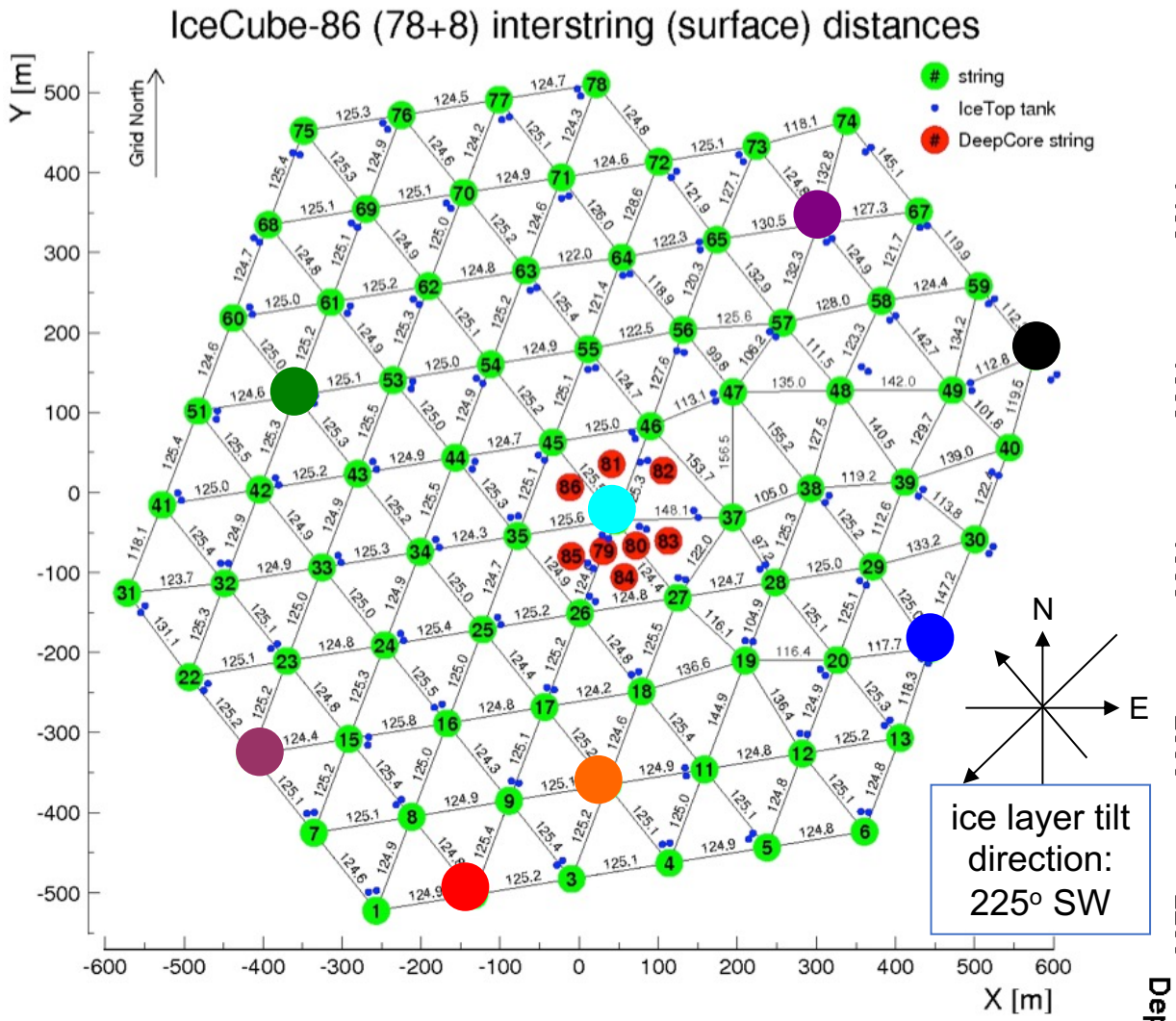


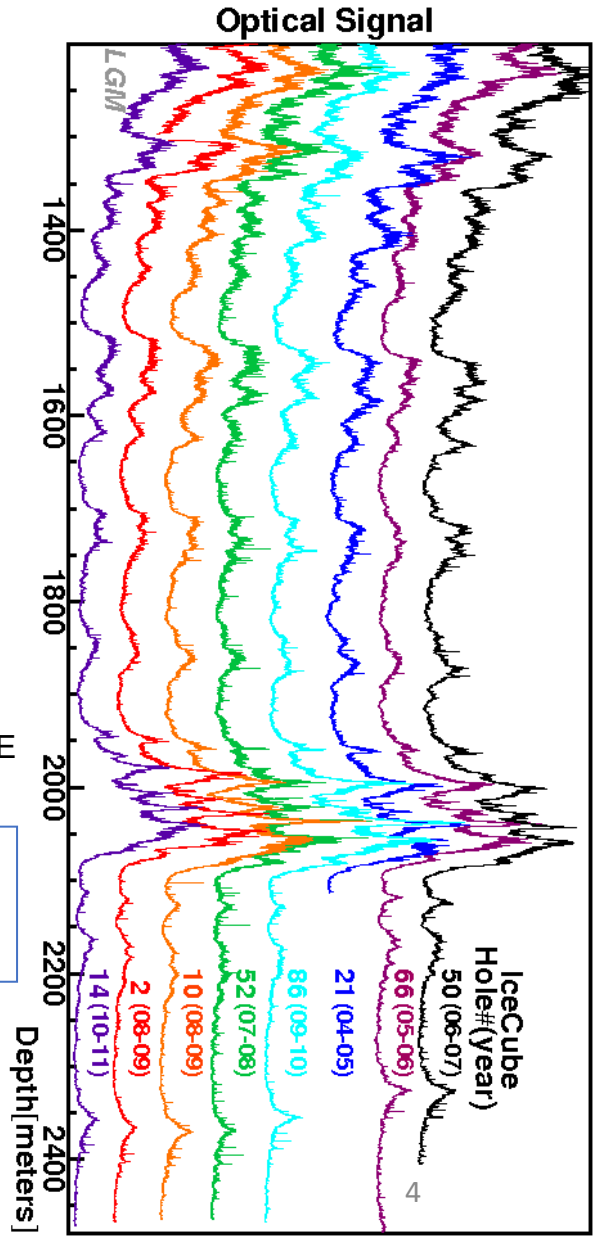




Dust logger mapping of the ice tilt

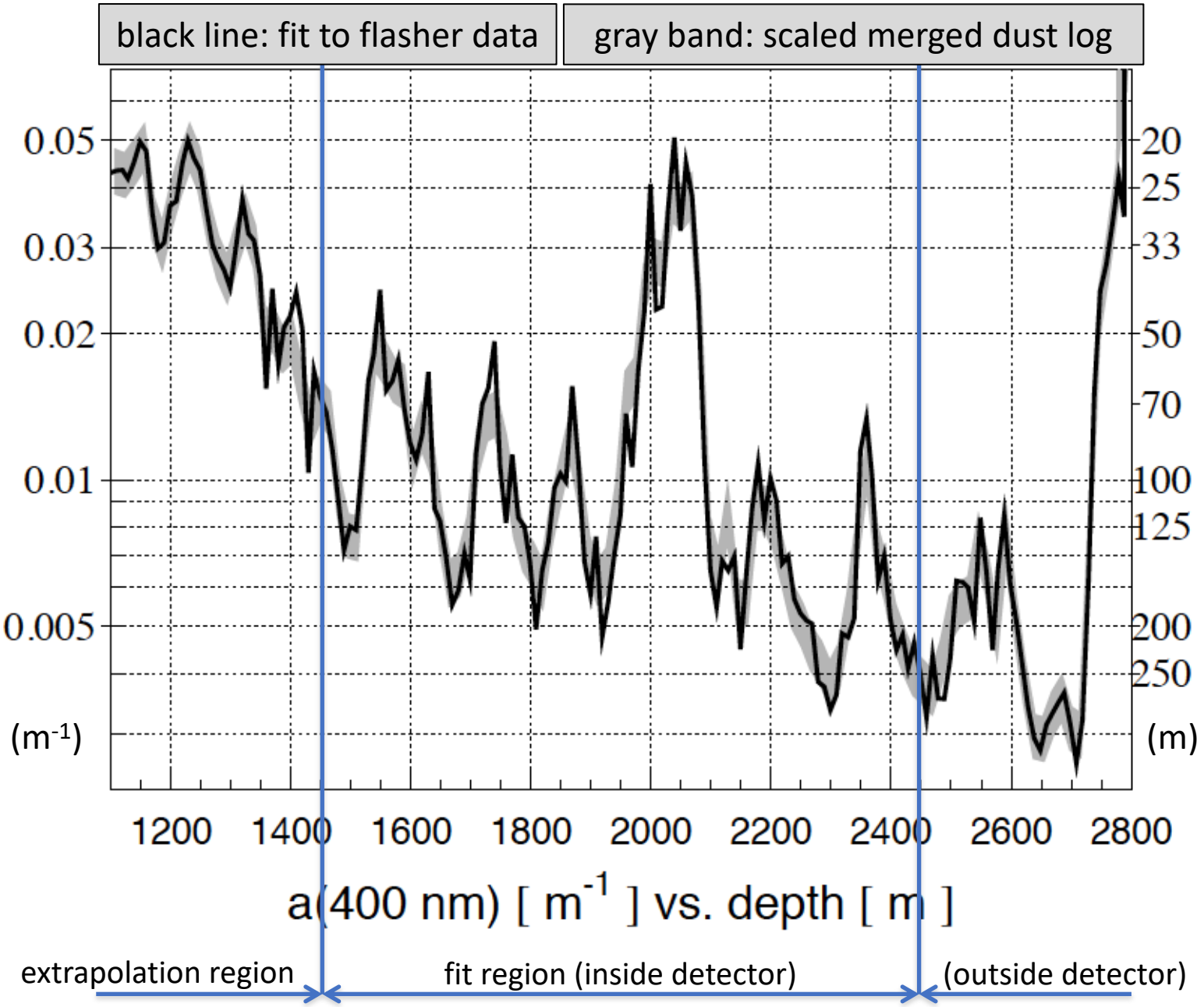


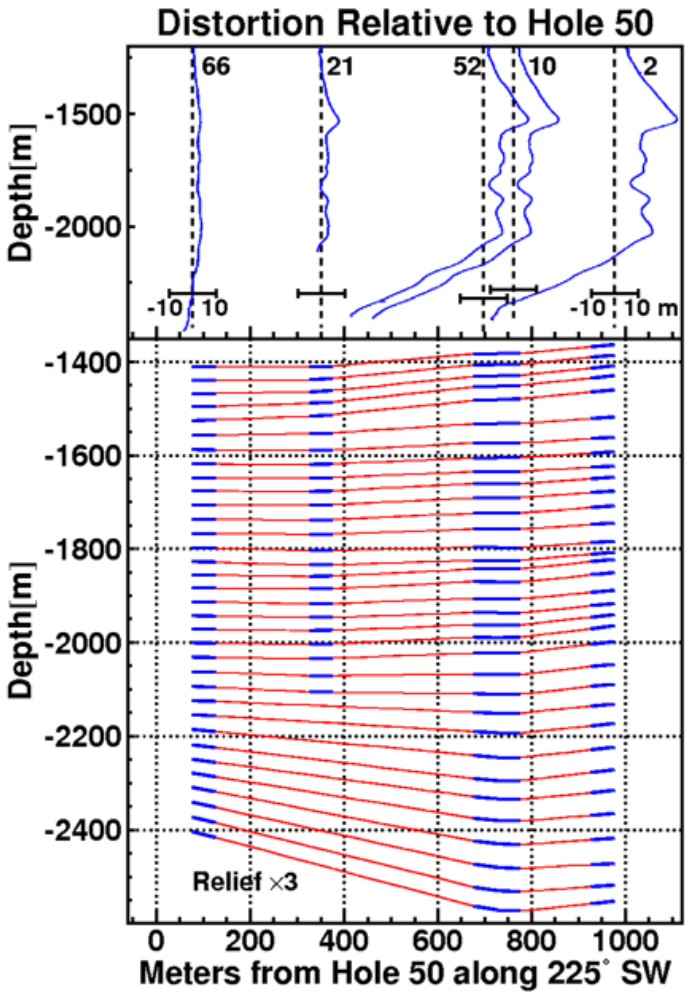




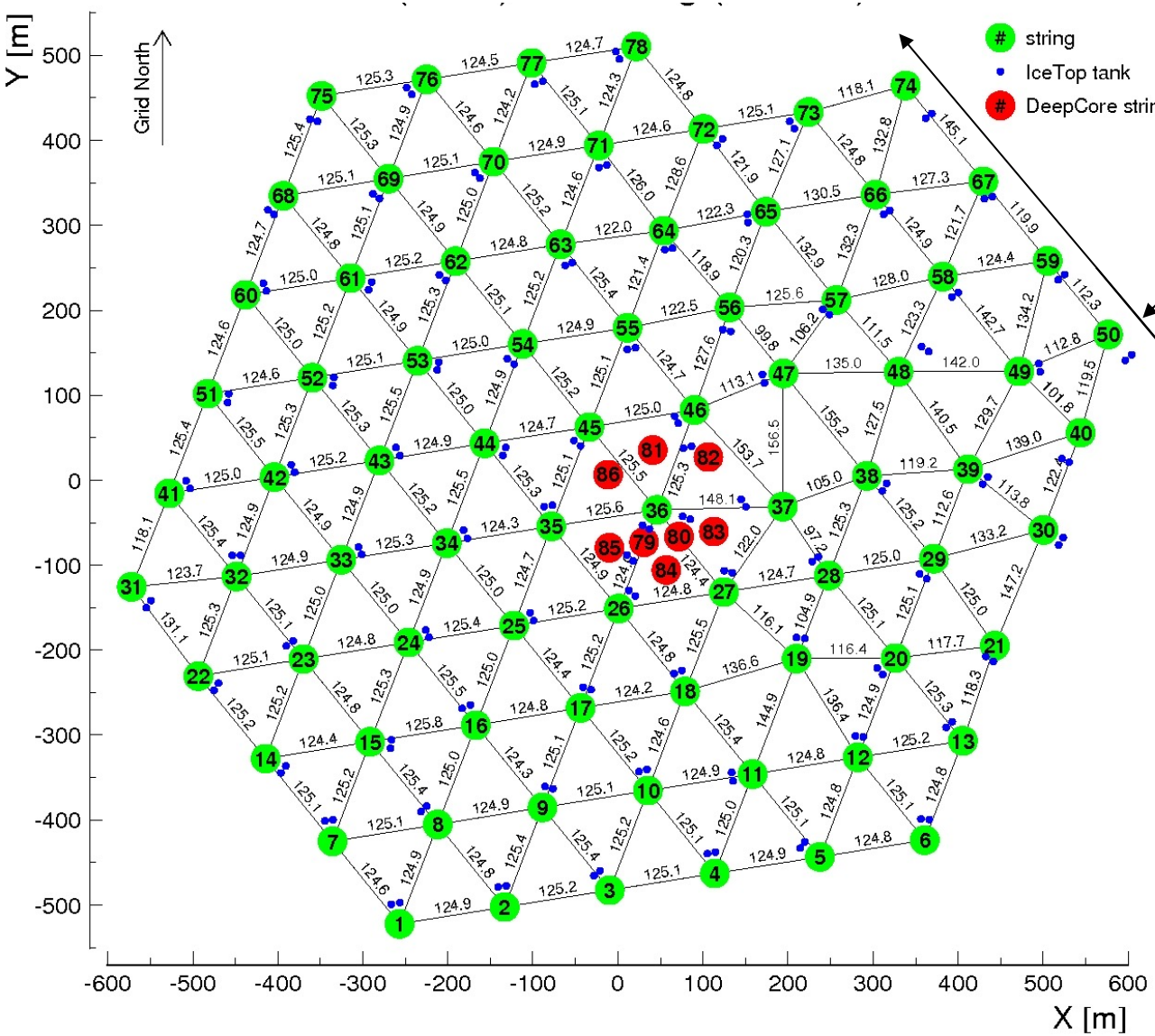
The ice layers (i.e. layers of ice with similar optical properties) change in depth by as much as 60 m when going from NE to SW corners of the detector

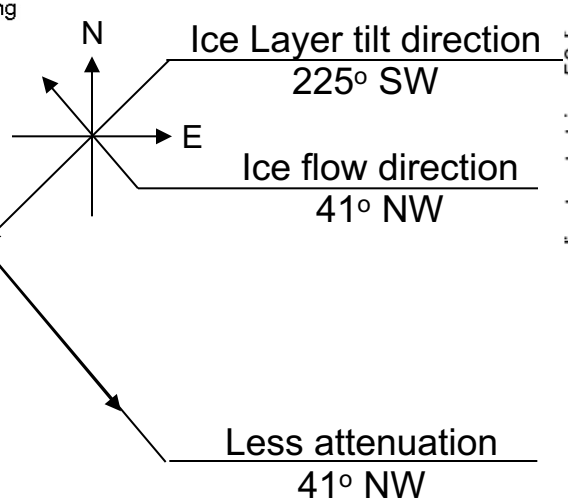
Correlation of fitted optical properties with dust logger data

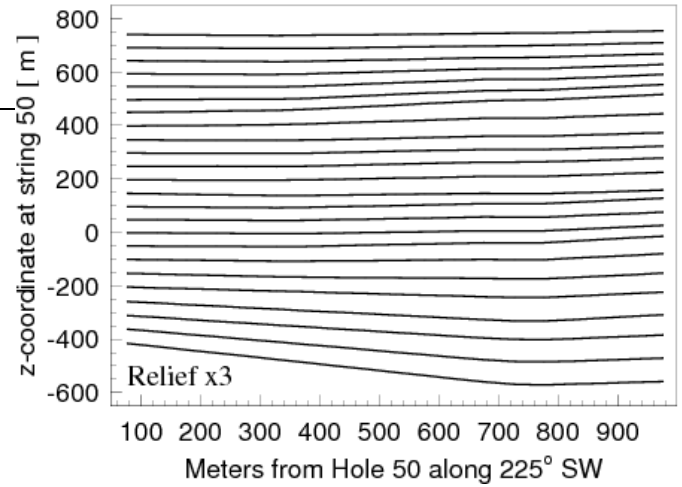


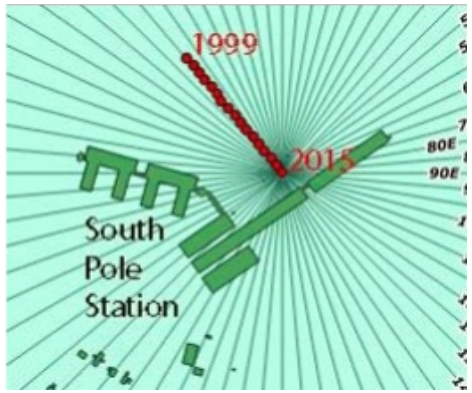


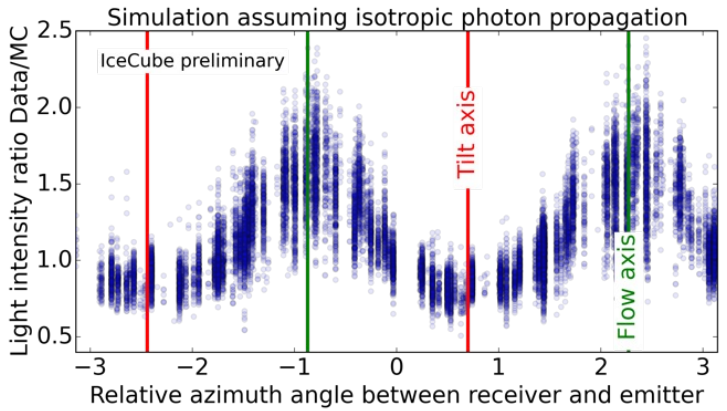
Glacial ice flow, ice layer tilt, and optical anisotropy











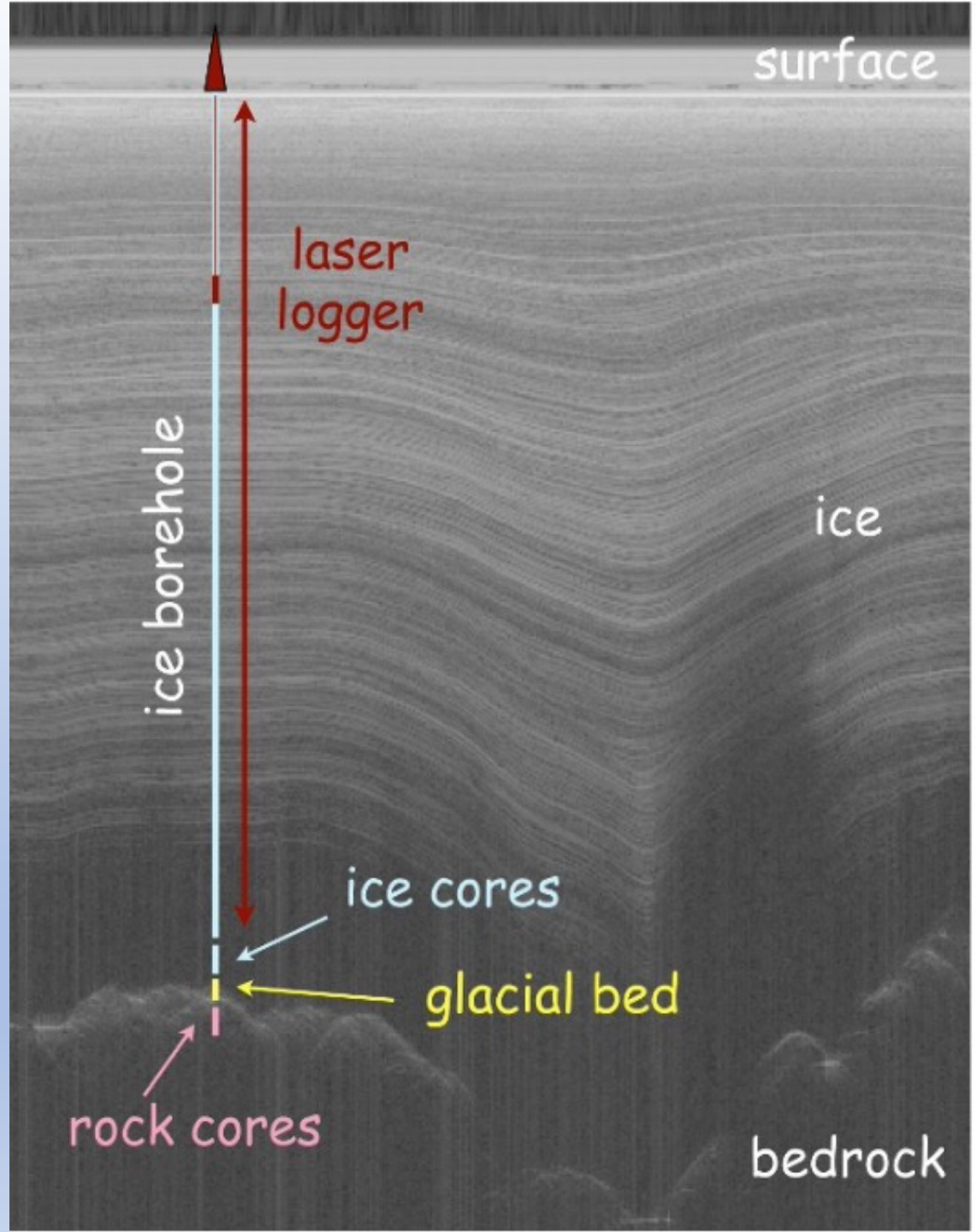
Ice tilt concept

Ice at the South Pole is flowing downhill at a rate of ~10 m/year

While the surface of the ice is flat, the bottom of the ice sheet rests atop of bedrock, which has irregular features such as hills and valleys

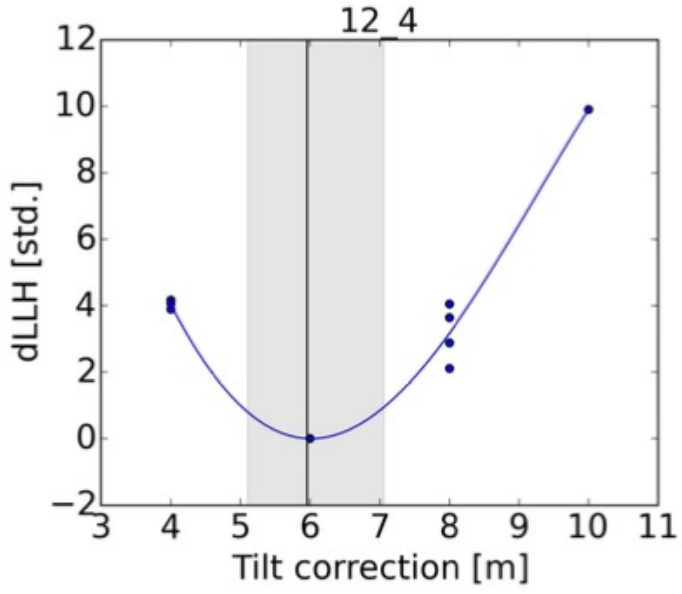
The ice sheet deforms as it flows through these features, and this results in lower ice layers following the shape of the bedrock; the closer to bedrock, the more the ice layers deviate from the flat that we see on the surface

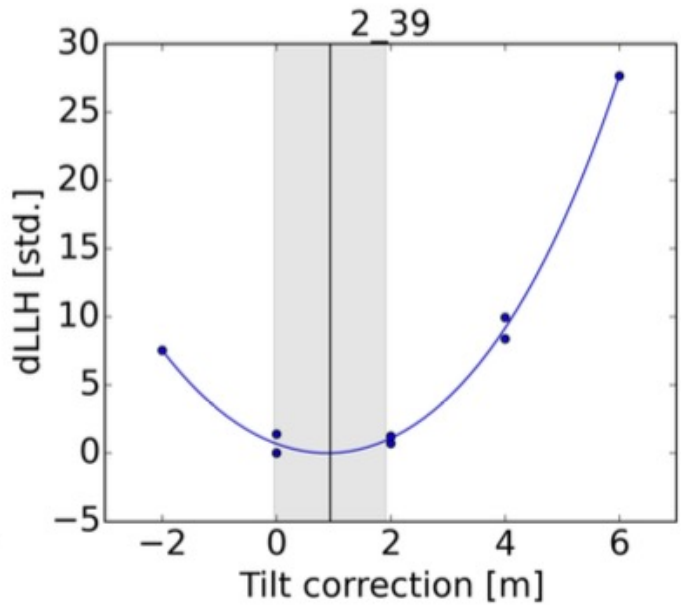
An ice layer consists of ice deposited at around the same time, so should have the same concentration of impurities across the layer, thus same scattering and absorption properties. The "dirtier" layers will create bands of reflected radar signal

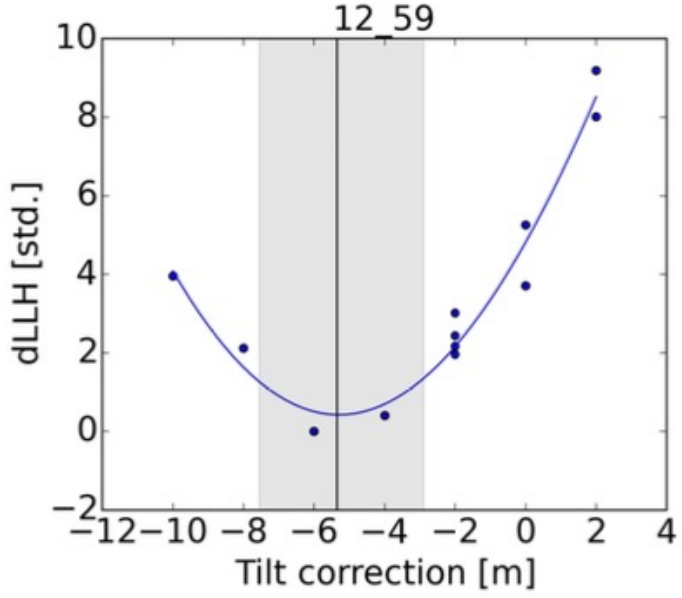


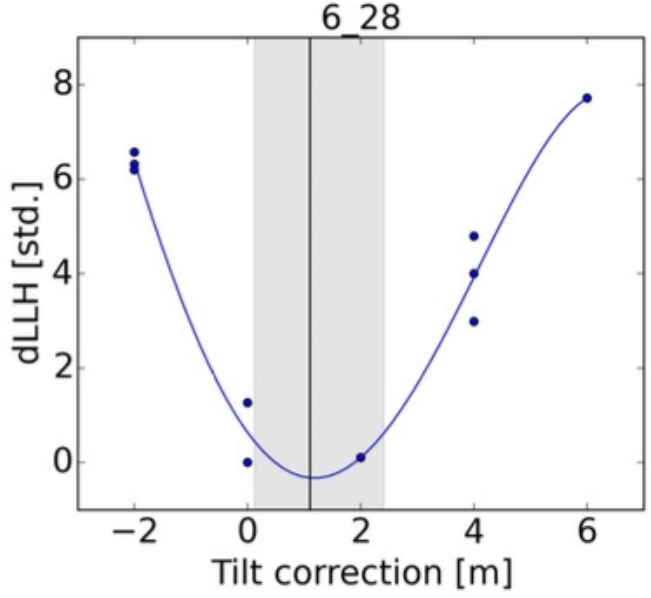
Per-DOM flasher fits

- Tilt correction in the vicinity of each DOM fitted by globally shifting the stratigraphy when optimizing its emitter flasher LLH
- Statistical uncertainty ~1m
- Extremely simple & quick fit, but with large individual biases, & methodological inconsistencies
  (reference stratigraphy no longer applicable)

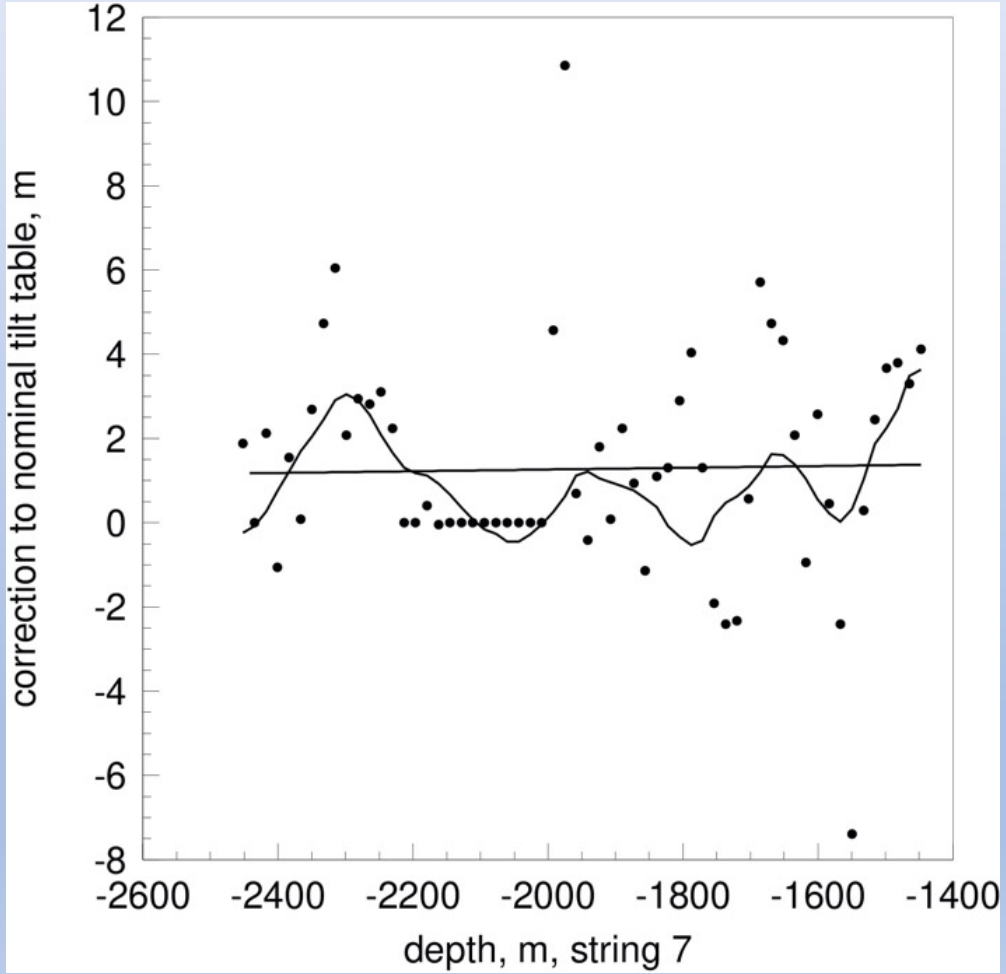






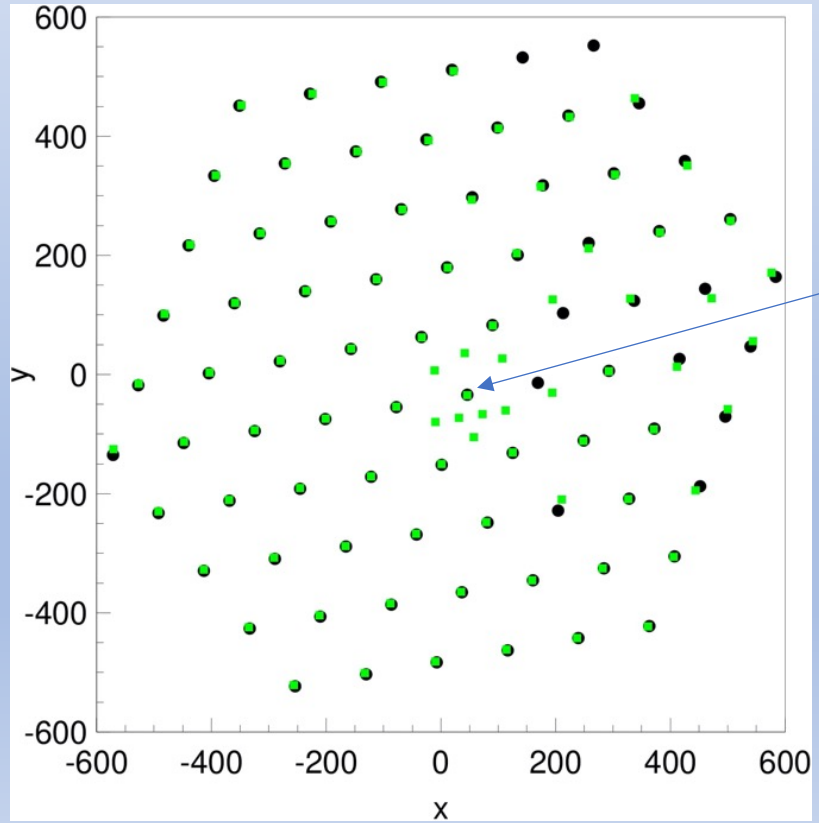


Tilt parameterization



The per-DOM corrections were smoothed (per-string and vs. nearby strings)

and extrapolated to nearby points of a regular grid roughly matching the outline of IceCube detector.



Nominal ice table given at this location

Here the depth shifts due to tilt are set to 0

Combined tilt+ice table fit

The initial solution so obtained was further refined with a combined ice and tilt iterative fit.

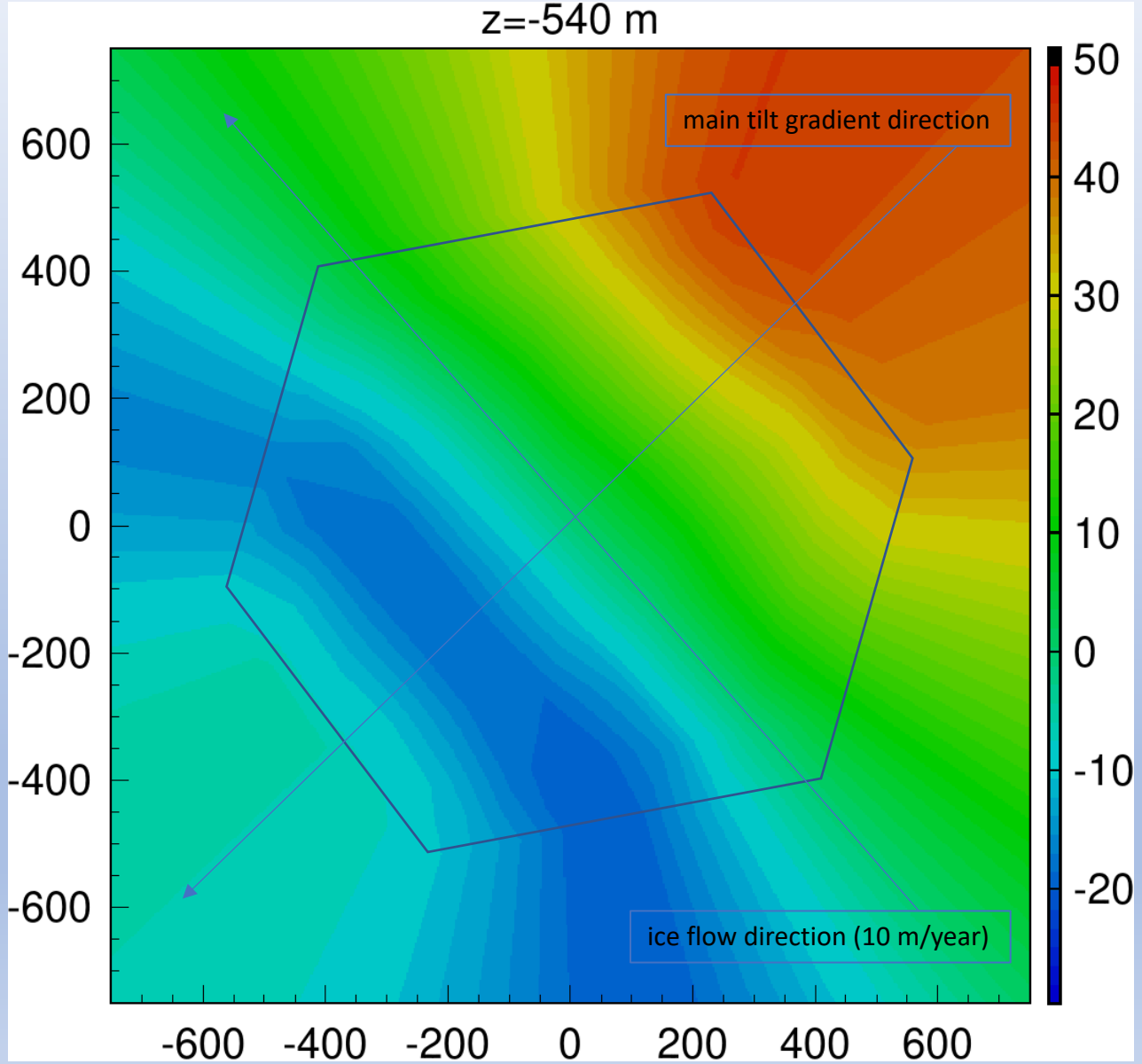
For each iteration, ~100 smoothed random variations of the ice and tilt tables were simulated and compared with flasher data.

The comparison function (likelihood) in the space of 10388* varied parameters was then fitted with a gradient descent method to a paraboloid to find the best point.

To stabilize the search, we had to explicitly enforce positive-definite nature of the paraboloid, and impose some regularizations (e.g., to make the paraboloid at flat as possible, while still going through the points).

*) 10388 = (80-1) tilt grid points * 125 depth points + 3 ice parameters (scattering, absorption, and anisotropy strength) * 171 depth points

Ice tilt fitted with IceCube calibration data



Regions outside of detector hexagon outline are extrapolations

Regions above and below +-500 m are outside the detector volume, and as such, are also extrapolations

Shown are ice layer shifts wrt. a point near string 36 (close to detector center)

The 1d gradient tilt (only accounting for tilt in the direction NE-SW) appears to be a better approximation at the bottom of the detector

Across the entire fitted depth range there appears to be an additional component that changes the depth of ice layers along the ice flow (layers getting shallower downstream)

Backups: birefringence slides from last time

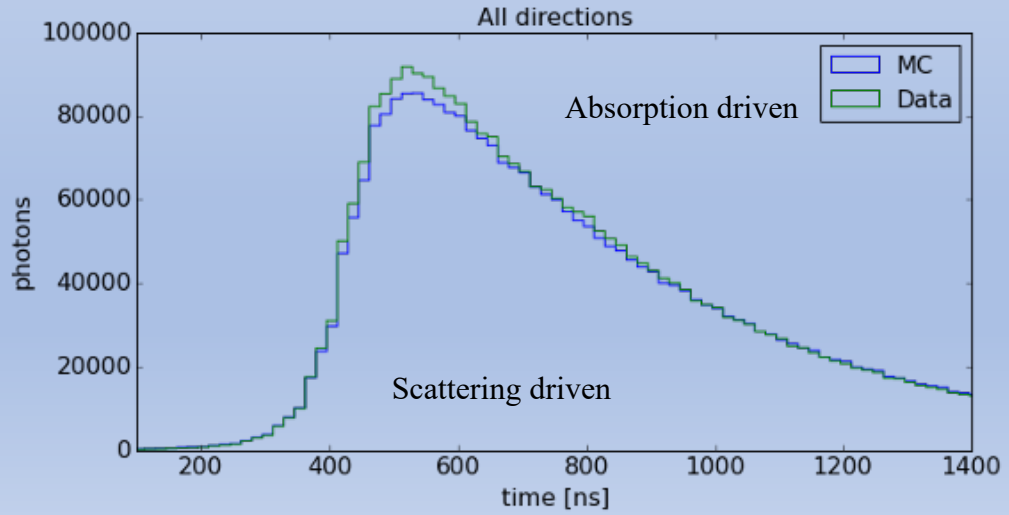
Models of optical ice anisotropy in IceCube

1. Scattering (mainly): direction dependent scattering function (ICRC 2013)
2. Absorption (mainly): direction dependent absorption (studied in 2018)

Introduced depth-dependence (2017)

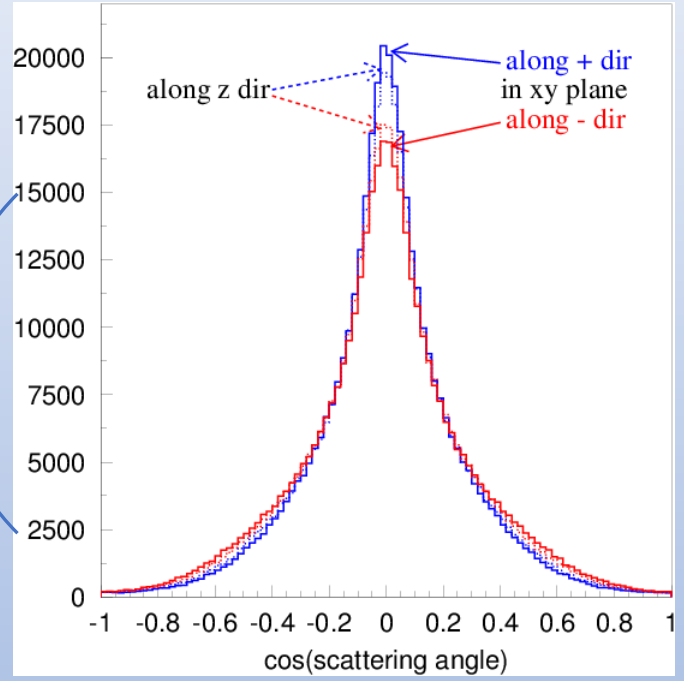
Discrepancies between data and simulation remain

Cannot simultaneously fit total charge and
arrival time distribution to statistical precision



scattering-based

SPICE Lea, 3.2.x

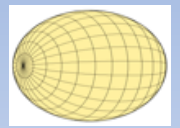


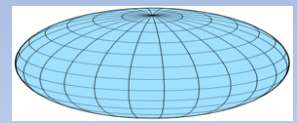
absorption-based

SPICE EMRM

prolate

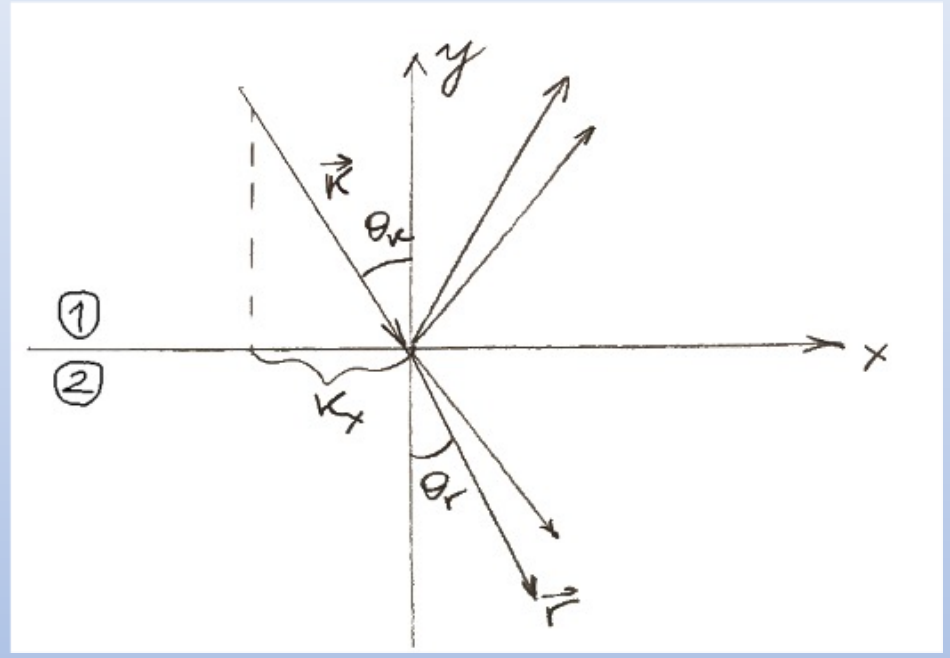
oblate





Birefringence

- Ice is a birefringent material with n_e-n_o=0.0015. This tiny difference builds to a macroscopic effect due to 1000s of ice crystal boundaries crossed per meter of traveled distance
- At each grain boundary every ray is split into two reflected and two refracted rays, one ordinary and one extraordinary ray each
- Wave vector component parallel to surface is conserved, norm is proportional to the refractive index
- Poynting vectors are derived from wave vectors and boundary conditions
- Outgoing ray is randomly sampled from Poynting vectors according to Poynting theorem (Poynting vector component through the plane is conserved)



$$\begin{aligned}
\hat{n} \cdot \boldsymbol{D}_2 &= \hat{n} \cdot \boldsymbol{D}_1 \\
\hat{n} \cdot \boldsymbol{B}_2 &= \hat{n} \cdot \boldsymbol{B}_1 \\
\hat{n} \times \boldsymbol{E}_2 &= \hat{n} \times \boldsymbol{E}_1 \\
\hat{n} \times \boldsymbol{H}_2 &= \hat{n} \times \boldsymbol{H}_1.
\end{aligned}$$

Hence we can make the following observations:

1. Normal components of $\boldsymbol{D}$ and $\boldsymbol{B}$ are continuous across a dielectric interface
2. Tangential components of $\boldsymbol{E}$, $\boldsymbol{H}$ are continuous across a dielectric surface

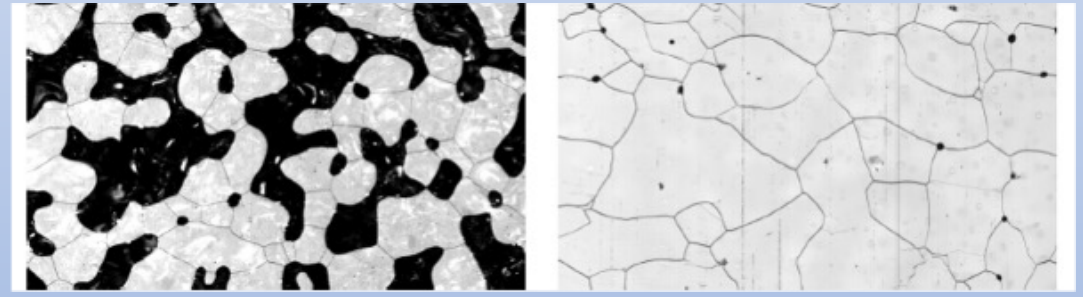
Scattering patterns birefringent ice

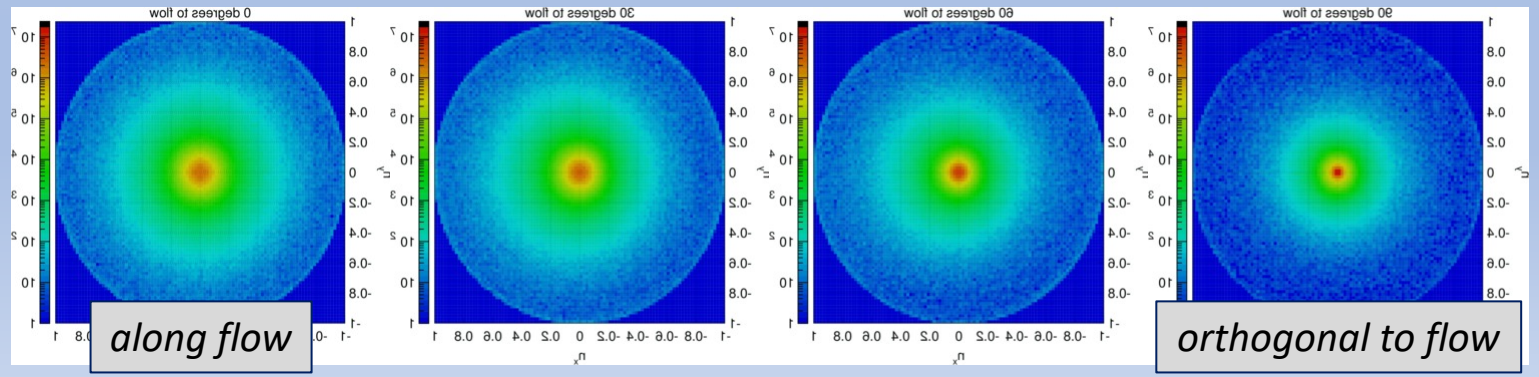
Running MC simulation with realistic crystal size, elongation, and orientation distributions (correlated to flow direction):

Diffusion is largest on flow axis and smallest orthogonal to it

Photons on average get deflected towards the flow axis

→ photons effectively fly a curve towards the flow axis

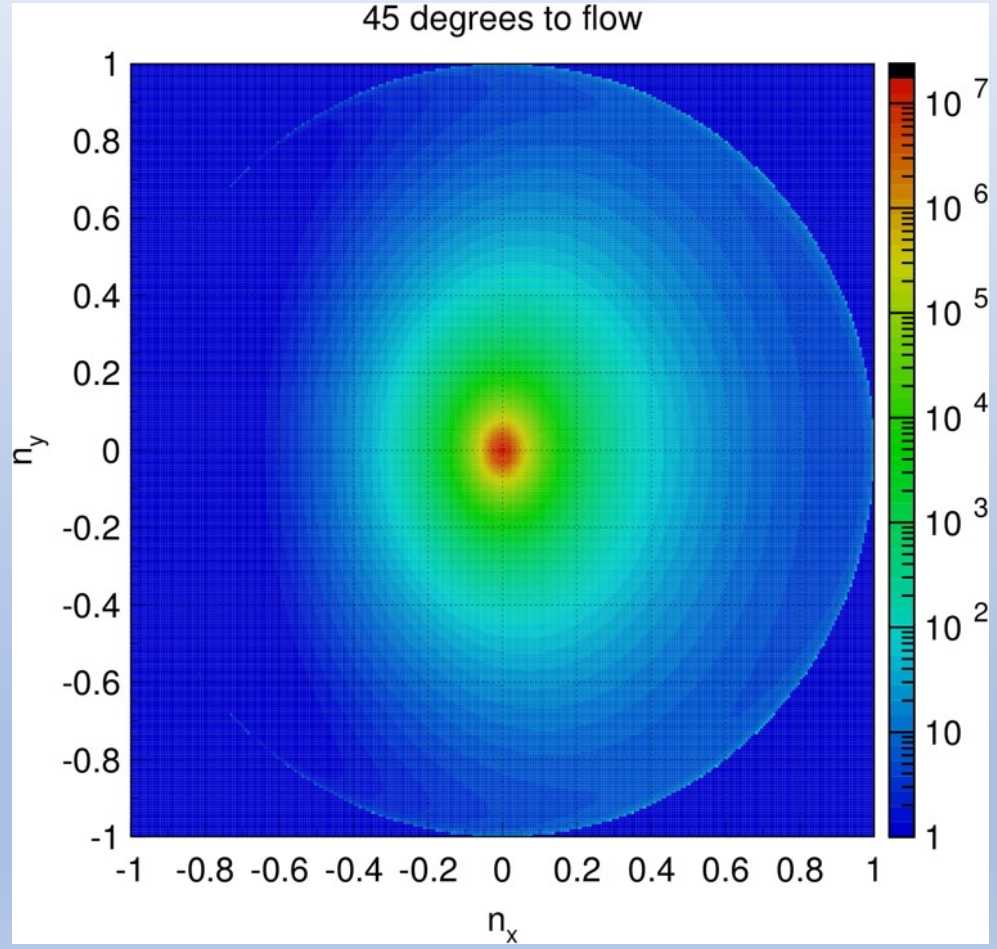




along flow

orthogonal to flow

after ~ 1 m of propagation:



towards flow

Ice crystal grain size vs. depth

- Due to the assumptions on unconstrained parameters (elongation, absorption anisotropy…) the size has an overall scaling uncertainty
- The fixed parameters (such as fabric) may also bias the result
- Still we see that grain size increases with depth and in particular below the dust layer
- Grain size seems to be anticorrelated to scattering
  → crystals are smaller where scattering is stronger, i.e., where there is more dust

